A Snow Index for the Landsat Thematic Mapper and Moderate Resolution Imaging Spectroradiometer

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Appendix I

ABSTRACT

This paper describes the snow mapping algorithm being developed for use with the Earth Observing System (EOS) MODerate resolution Imaging Spectroradiometer (MODIS). A key component of this snow mapping algorithm is the normalized difference snow index (NDSI). The NDSI employs Landsat Thematic Mapper (TM) visible (0.56 μm) and near-infrared (1.65 μm) data. The snow algorithm uses the NDSI in combination with near-infrared reflectance to identify snow cover and discriminate snow from clouds. The NDSI-based snow algorithm functions with a simple set of decision rules for snow, and can be run in an automated fashion on any TM scene without *a priori* knowledge of surface characteristics. Consistent identification of snow cover in a variety of TM scenes has been attained with the algorithm. Snow mapping results from TM imagery of the Glacier National Park, Montana region are presented. This algorithm is expected to generate global snow cover data products in the EOS era beginning in 1998.

INTRODUCTION

Snow is an important component of the global hydrologic cycle. Changes in amount and extent of snow may accompany global climate change. Monitoring of global snow cover is possible with satellite-borne sensors that observe the Earth's surface. Data sets of snow cover that are years to decades in length may be constructed from satellite sensors. NOAA has generated a Northern Hemisphere Weekly Snow and Ice Cover Chart since November 1966 (Matson, et al., 1986) from the Advanced Very High Resolution Radiometer (AVHRR) and predecessor sensors. Also, the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) has been used to generate global data sets of snow cover (Chang et al., 1987). The MODerate resolution Imaging Spectroradiometer (MODIS), a part of the Earth Observing System (EOS), will provide the capability to monitor snow cover globally beginning in 1998 with launch of the first EOS platform. The additional bands and better spectral and spatial resolutions relative to the AVHRR should permit improved mapping of global snow cover using MODIS data.

Our efforts are focused on prototyping the MODIS snow cover algorithm (SNOMAP) for generation of a global snow cover data product in the EOS era. Development of SNOMAP is done principally with Landsat Thematic Mapper (TM) data. Some development has also been done with Advanced Very High Resolution Radiometer (AVHRR) data, and MODIS Airborne Simulator (MAS) data but is not reported here. Use of several sensors to develop SNOMAP is required because no currently-orbiting satellite sensors have the MODIS spectral and spatial specifications.

MODIS

MODIS is designed to measure biological and physical processes on a global basis every one to two days. A MODIS instrument is planned for both the EOS-AM and -PM satellite platforms. MODIS will provide long-term observations of the Earth for study of global dynamics and processes occurring on the surface of the Earth and in the lower atmosphere. MODIS employs a conventional imaging radiometer concept, consisting of a cross-track scan mirror and collecting optics, and a set of linear detector arrays with spectral interference filters located on four focal planes. The optical arrangement will provide imagery in 36 discrete bands between 0.4 μm and 15.0 μm. Bands were selected for diagnostic significance in earth sciences (Salomonson and Toll, 1991). Wavelength center locations and spatial resolutions of MODIS bands that have corresponding TM coverage are given in Table 1. Because of the narrow spectral bands and differing spatial resolutions of MODIS there is band overlap with some of the broader spectral bands of the TM.

Table 1. Corresponding MODIS and TM wavelengths (bands).

MODIS Band	Spatial Resolution (m)	Center Wavelength (μm)	Corresponding TM Band
1	250	0.645	3
2	250	0.858	4
3	500	0.469	1
4	500	0.555	2
6	500	1.640	5
7	500	2.130	7
13	1000	0.667	3

14	1000	0.678	3
16	1000	0.869	4
31	1000	11.030	6

Several calibration modules are part of the MODIS instrument that will perform in-flight calibrations. The Spectroradiometric Calibration Assemble (SRCA) will perform in-flight radiometric calibration checks, spectral band calibrations, spectral-band registration check, and self calibration. These in-flight calibration capabilities provide for well calibrated and characterized MODIS data.

Snow Reflectance Characteristics

Snow typically has high reflectance in the visible and near-infrared region of the spectrum. Fresh snow may reflect approximately 80% of incident solar radiation (O'Brien and Munis, 1975; Choudhury and Chang, 1981; Hall, et al,. 1990). Snow reflectance decreases as snow ages or becomes contaminated by deposition of aerosols, soot, pollen, etc. (Warren, 1982; Dozier, 1984), yet remains much more reflective than most other surfaces. In the infrared part of the spectrum, reflectance of snow decreases to a minimum at about 1.6 μm where absorption by snow dominates (O'Brien and Munis, 1975; Warren, 1982). The snow characteristics of high reflectance in the visible and low reflectance in the infrared can be used in combination to distinguish snow from many other surface features and clouds. The MODIS snow cover algorithm is based on these reflectance characteristics of snow.

MODIS SNOW COVER ALGORITHM

The purpose of the MODIS snow cover algorithm, SNOMAP, is to generate a snow cover data set useful in global change research, and earth processes studies. The snow cover data set will be generated in concert with other MODIS data sets, using automated techniques in the product generation system (PGS) of the Earth Observing Data and Information System (EOSDIS). The goal of SNOMAP development is to build a robust algorithm for global identification and mapping of snow cover. SNOMAP is designed to identify snow and discriminate between snow and clouds using physical measurements of reflected and emitted radiation. A criteria test technique for snow identification and snow/cloud discrimination is employed in SNOMAP. SNOMAP results are analyzed and evaluated with other snow data sets such as the National Weather Service, National Operational Hydrologic Remote Sensing Center (NOHRSC) snow data products and other snow-mapping methods.

Snow is identified with two criteria tests in SNOMAP, one is the Normalized Difference Snow Index (NDSI) test and the other is a near-infrared reflectance test. The initial step in SNOMAP is to convert TM digital numbers (DNs) to reflectances. Conversion to reflectances is done using the constants and equations of Markham and Barker (1986). The scene center solar zenith angle is used to calculate reflectances and it is the only scene parameter that needs to be input to run SNOMAP on any TM scene. In the final step the criteria tests are applied to each pixel in a scene and a snow or not snow 'map' is generated. The resulting 'map' of snow cover is all pixels that lie in the acceptance region of both criteria tests.

The cardinal test for snow in SNOMAP is a snow index that we have termed the NDSI. This NDSI is a prime indicator of high visible reflectance and low infrared reflectance, or strong absorptance, at about 1.6 μm that is characteristic of snow. For TM data the NDSI is expressed as; NDSI = (TM 2 (0.56 μm) - TM 5 (1.65 μm))/(TM 2 + TM 5). Dozier (1989) showed that this ratio, along with other criteria tests, could be used in an automatic snow mapping procedure. The criteria tests and results presented by Dozier (1989) were for TM images of the southern Sierra Nevada mountains. The near-infrared reflectance criteria test at 0.83 μm, TM band 4, is effective at separating snow from ice-free water bodies. A pixel is identified as snow if the results of both criteria tests lie within the intersection of the acceptance regions of these two criteria tests. This acceptance region is the snow region and is Cartesian quadrant I formed by the intersection of the acceptance thresholds (bold vertical and horizontal lines in Figure 1) of the two criteria tests.

In the visible region of the spectrum, is very difficult to distinguish many types of cloud from snow. But in the infrared region, cloud reflectance is typically much greater than snow reflectance especially at about 1.6 μm. This difference in cloud and snow reflectance characteristics at about 1.6 μm, where snow absorbs but clouds reflect, is used for snow/cloud discrimination (Allen et al., 1990, Dozier, 1989, Bunting and d'Entremont, 1982). The NDSI provides snow and cloud discrimination simultaneous with snow identification based on this difference. Not all clouds are discriminated, but many are and others may be discriminated by use of other MODIS bands in the future, including perhaps some thermal infrared bands.

Threshold values for the criteria tests have been selected based on reports in the literature and our analysis on many TM scenes (for example, in Minnesota, Montana, Alaska, California, Antarctica and Greenland). SNOMAP has been analyzed on TM images with and without snow cover. Testing and analysis have shown that a NDSI threshold for snow of 0.40 functions well as a universal threshold for identification of snow. This threshold value was settled on after varying the threshold and, when possible, validating results against other snow data sets. The threshold lies on a continuum, if the threshold is increased then the number of pixels identified as snow decreases, and errors of omission increase. If the threshold is lowered then the number of pixels identified as snow increases and errors of commission increase. The 0.40 criteria threshold was suggested by Dozier (1989) to be good for identifying snow; our research supports the use of that threshold value for snow.

The 0.40 NDSI threshold for snow does allow some highly-reflective surfaces such as mineral deposits and deserts to be misidentified as snow in some situations. Increasing the NDSI threshold for snow reduces this type of misidentification error, and it may be possible that other criteria tests need to be developed to avoid these types of errors. Few other surface features exhibit a reflectance pattern similar to snow across the visible, near-infrared, and infrared parts of the spectrum, although bright surfaces such as deserts and some highly-reflective mineral deposits may be confused with snow in some situations.

The near-infrared reflectance test is necessary to discriminate between ice-free water bodies and snow which were confused with snow when the NDSI was used alone. Water bodies typically have low reflectance but exhibit high NDSI values, which caused them to be identified as snow based on the NDSI value alone. That confusion was eliminated by using the criteria test for high near-infrared reflectance to separate ice-free water bodies from snow. The threshold reflectance value used for the near-infrared test is 0.11.

Separation of snow, cloud, rangeland, and forest by the combination of criteria test is distinct (Figure 1). Samples in Figure 1 were extracted from a 14 March 1991 TM scene of

Glacier National Park, Montana, except for the sample labeled forest (summer). Because there was no snow-free forest in the 14 March 1991 scene, a forest sample at the same location was extracted from a 3 September 1990 TM image that had no snow so that the snow-free and snow-covered forest sample could be compared. In Figure 1 the open diamonds are a sample from the snow-covered surface of Lake McDonald, a large lake in Glacier National Park; open triangles are a sample from snow-covered southeast-facing mountain slopes that saturate TM bands 1,2, and 3. SNOMAP criteria test threshold values for snow are shown as bold horizontal and vertical lines in Figure 1; any pixel that lies in Cartesian quadrant I formed by the intersection of the threshold lines is considered as snow. Snow lying on the shadowed slopes of mountains exhibits a high NDSI value even though it has low reflectance in visible and near-infrared wavelengths and is generally identified as snow (sample not shown). SNOMAP identifies pixels that have reflectance characteristics dominated by snow. Pixels that are identified by snow may be entirely snow covered or may be fractionally snow covered to an unknown extent.

Identification of partial snow cover on the landscape or snow cover under forest canopies are challenges in mapping snow cover. Our research suggests that snow effectively dominates the reflectance properties of a surface when it is present in some amount. The amount of snow cover necessary for snow to dominate the signal from a pixel is undetermined. As an example, the winter forest sample from Glacier National Park (Fig. 1) is identified mostly as snow in the 14 March 1991 scene when it was known that the ground was snow covered. Forest was identified as snow primarily because the NDSI value was characteristic of snow. Yet not all pixels in that sample were identified as snow. That indicates that there is possibly a relationship between canopy density, canopy structure, and amount of snow present. In the summer forest sample no pixels were identified as snow because the NDSI was not characteristic of snow, and there was no snow present in the forest at that time.

Initial comparison of SNOMAP with other snow mapping methods and snow cover data sets indicate that SNOMAP is capable of generating reasonably accurate and reliable results for mapping of snow cover.

SUMMARY

The snow mapping algorithm, SNOMAP, has proven to be reliable at identifying snow cover in many different areas observed by the TM. The NDSI has been demonstrated as a prime indicator of snow, and when combined with other tests, an automatic snow mapping algorithm is emerging. Challenges to improving SNOMAP are to determine quantitative estimates of accuracy of the algorithm in mapping snow extent and to understand how to scale the algorithm up to MODIS spatial resolutions of 250 m, 500 m, and 1000 m and to scale from there to create a global snow-cover data set. There are also other challenges including improving snow/cloud discrimination, and modifying SNOMAP for generation of a global snow cover data set, not discussed in this brief paper. The objective is to develop a dependable snow mapping algorithm for generation of a global snow cover data set in the EOS era. The MODIS snow-cover data set will be a complement to other snow-cover data sets, such as the NOAA snow-cover data set and those generated using passive microwave data. These are intended to increase understanding of the role of snow in global cycles and global climate change, and to permit improvement in snowmelt-runoff forecasting.

Acknowledgements

We extend our thanks to Joseph White, University of Montana, for providing summer imagery of the Glacier National Park, Montana region.

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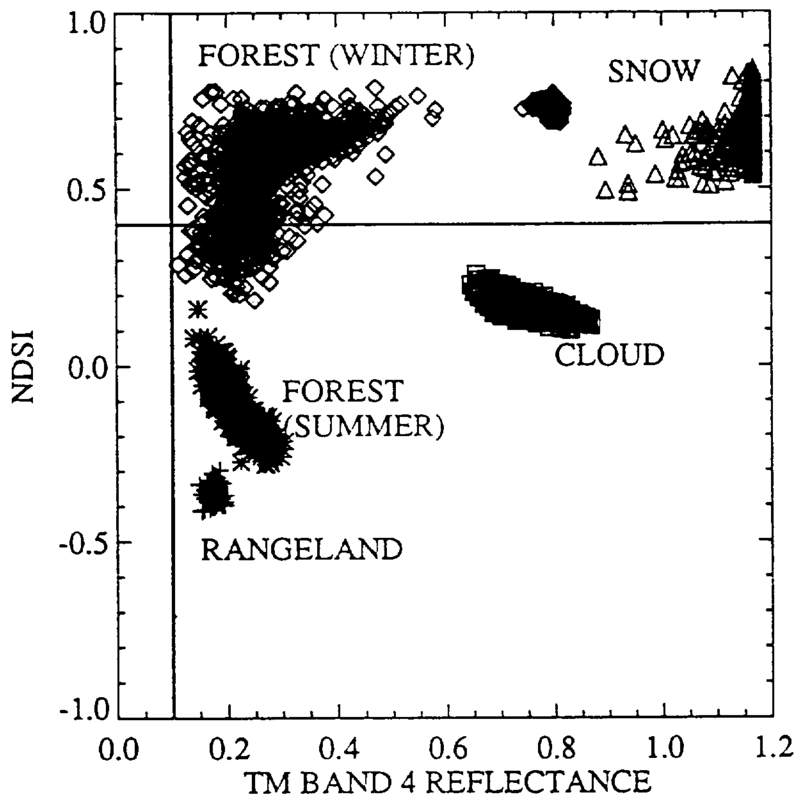
Figure 1.
Feature samples from 14 March 1991 Landsat TM scene of
Glacier National Park, Montana, region.



FOREST (WINTER)
SNOW
CLOUD
FOREST
(SUMMER)
RANGELAND
NDSI
TM BAND 4 REFLECTANCE
1.0
0.5
0.0
-0.5
-1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2